UNDERWATER RESEARCH METHODS FOR STUDY OF NUCLEAR BOMB CRATERS, ENEWETAK, MARSHALL ISLANDS

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Three craters, created by the explosion of nuclear fusion devices, were mapped, sampled, core drilled and excavated with airlifts at Enewetak Atoll in the Marshall Islands by using scuba and a research submersible. The craters studied were Mike, Oak, and Koa. Tests took place near sea level at the transition between lithified reef flat and unlithified lagoonal sediments, where water depths ranged from 1 to 4 m. Craters produced by the blasts ranged from 30 to 60 m in depth. The purpose of our study was to determine crater diameter and depth immediately after detonation. Observations of submerged roadways and testing structures and upturned crater rims similar to those characteristic of meteor impacts indicate that the initial, or transient, craters were smaller than their present size. At some later time, while the area was too radioactive for direct examination, the sides of the craters slumped owing to dewatering of underlying pulverized rock. Core drilling of crater margins with a diver-operated hydraulic coring device provided additional data.

On the seaward margin of the atoll, opposite Mike, a large portion of the atoll rim approximately the size of a city block had slumped into the deep ocean, leaving a clean vertical rock section more than 400 m high. An abundance of aggressive grey reef sharks displaying classic territorial behavior prevented use of scuba at the Mike slump site. The two-person submersible R. V. Delta *provided protection and allowed observations down to 300 m. During the 6-week period of study, we made more than 300 scuba and 275 submersible dives. Mapping was with sidescan sonar and continuous video sweeps supplemented by tape-recorded verbal descriptions made from within the submersible. A mini-ranger navigation system linked to the sub-*

mersible allowed plotting of bottom features, depth and sediment type with spatial accuracy to within 2 m.

INTRODUCTION

Between 1952 and 1958 the United States conducted atomic testing at Enewetak Atoll (Figure 1). The first fusion bomb, a 10.4-megaton-yield device called Mike, was detonated on a small island there on October 31, 1952. Two subsequent devices, Oak and Koa (8.9 and 1.4 megatons, respectively), were detonated at Enewetak. Koa, a relatively small device, was detonated May 12, 1958, on a sand spit adjacent to Mike, and Oak was detonated June 28, 1958 on a barge in 4 m of water, (Figure 2). All the tests were on or near the lagoonal margin of cemented reef flats, also called reef plates, a location that made the object of our mission doubly difficult.

Lagoonal sediments consist of soft muds and uncemented sands, and the transition from reef flat-rock to lagoonal sediment is abrupt. The devices were tested at or near the point of transition from shallow rock to relatively deep soft bottom.

In 1984 the Defense Nuclear Agency (DNA) contracted with the U.S. Geological Survey (USGS) to determine the transient dimensions of craters produced by the Oak and Koa devices. Transient craters are those created at the instant of detonation. The Oak and Koa craters that exist today are larger (1,750 and 1,316 m diameter), however, due to the gradual subsidence of fractured rock and dewatering of compacted sediment. Special techniques and methods had to be developed to determine the transient dimensions, which existed unseen by nuclear physicists when the area was inaccessible and obscured by milky contaminated seawater.

Measuring transient-crater dimensions would have been relatively simple had the tests occurred on land. Post-event subsidence would have been minor. At Enewetak not only were the sediments water saturated, but also there were differences in water depth and profound geological differences between reef flat and lagoon. Our work was further complicated by crater depth (Oak is 60 m deep) and abundant grey reef sharks in certain areas, and the location is far removed from mainland supplies.

The purpose of this paper is to describe methods and equipment used to overcome various problems related to this remote location.

METHODS

A diagnostic product of large impact or explosive craters is upturned or overturned flaps. These flaps are formed when explosive forces push material upward and outward, causing rock layers at the crater margin to turn away and fold back on themselves. An up- or overturned flap buried within a larger crater would therefore approximate the transient-crater margin that formed before significant subsidence began.

The distribution and age of ejecta, i.e., the material excavated and thrown from the crater by the blast, can also help determine the depth and lateral extent of a transient crater. Radially oriented rays of ejecta, called ejecta rays (Figure 3), do not exist within craters but originate at the crater margin. The common point of ejecta-ray origin can therefore help delineate the transient-crater margin. Isotopically and paleontologically determined ages of ejected material can be used to determine the depth of excavation.

Methods and equipment used to search for upturned flaps and to map ejecta included: 1. scuba, 2. a two-person research submersible, 3. an underwater core drilling apparatus, and 4. airlifts. These methods were used in conjunction with sidescan sonar mapping and subbottom profiling. Underwater video films and photographs were also extensively used in the mapping effort. A possible upturned flap was located and exhumed with an airlift by scuba diving in Oak crater and a fortuitous discovery of sunken manmade objects in Koa crater provided direct evidence of post-event subsidence.

Mapping

Mapping within the craters, because of depth (up to 60 m), and navigational requirements, was accomplished from within the research submersible *Delta*. Navigation was provided by a mini-ranger system linking the mother ship, a 50-m supply boat, to precisely located transmission towers on nearby islands. The ship location was continuously plotted to within a 2-m accuracy. The supply boat was linked with the submersible via transducers and a track point system. By use of a computer, the submersible's position could be continuously plotted on board the surface vessel.

Inside the submersible, the observer took continuous video images of the bottom and recorded verbal observations on the sound track and, as backup, on a separate tape recorder. An in-camera digital clock linked the time of observations and video images with the submersible's plotted position aboard the surface vessel. Visibility was generally in the 10- to 20-m range, thus a 10- to 20-m-wide swath of observation was recorded during each submersible transect. By criss-crossing the crater, sediment and biotic changes were noted and charted until a consistent pattern emerged. An example from Oak crater is shown in Figure 4. Figure 5 is an "air-brush" interpretation of bottom configuration at Oak crater based on diving observations and sidescan sonar surveys. Similar maps and interpretations were made for Koa and Mike craters (Folger, 1986).

Research Submersible

In addition to mapping, the submersible played another vital role in our research at Enewetak. When the Koa device was fired adjacent to the crater previously produced by Mike, the reef flat was so violently shaken that a large portion of the outer reef edge, more than 10^8 metric tons, sheared off and slumped to oceanic depths (Figure 6), leaving a cirque-shaped submarine scarp extending more than 190 m into the reef. The outcrop afforded an unparalleled opportunity to collect samples and make observations on atoll reef growth. We initially attempted to examine the wall using scuba but were forced from the water by dozens of grey reef sharks displaying classic territorial defense posture.

From within the safety of the submersible, we were able to collect rocks along the wall to a depth of 400 m. The site proved to be a unique opportunity for reef studies because the wall was not encrusted and had an appearance not unlike the walls of a typical limestone quarry (Figure 6). The exposure clearly demonstrated how the outer margin of the atoll is armored by submarine cemented reef framework, an example of the "bucket of sand" hypothesis proposed by Schlager (1981). The "bucket of sand" hypothesis states that carbonate platforms and atolls are aided in their growth and become preserved in the geologic record because cemented marginal reefs grow upward faster than relative sea level rises, thus producing a "bucket" in which biogenic sediment accumulates.

Samples of reef rock were sampled to 400 m below sea level (Halley and Slater, 1987). This kind of detailed sampling could not be accomplished without a manned submersible.

Scuba

Scuba diving played an important role along the shallower crater margins. Diving along the reef-flat side of Oak crater revealed an upturned rock ledge (possible upturned flap) that airlifting and core drilling (see Figures 7 and 8) showed was composed of reef-flat rock, which is exposed at low tide elsewhere along the reef. Core material and airlifting sand from the upper surface of the rock, (Figure 9) were critical to confirmation of the origin and nature of this rock. In places, the rock layer, once at low tide-level, had been depressed to as much as 60 m below low tide.

Scuba diving was particularly important to the interpretation of transient-crater diameter in and adjacent to Koa crater. During routine submersible video mapping, we located and plotted the position of several railroad rails, which stood vertically in the sediment. Investigation by scuba diving later revealed a fence-like row of 28 rails leading toward the center of the 30 m-deep crater. The rails were bent away from "ground zero" and formed a line 46 m long that began in 15m of water near the crater margin and extended out to a depth of 18 m. Excavation along the rail line with a 15-cm diameter airlift uncovered buried timbers and rip-rap. The origin of the rail line was a mystery until examination of Air Force documents and old aerial photography showed that the rails were part of a roadway constructed across the reef flat to provide access to the small island where the Mike device had been detonated. The road was constructed by driving rails into the reef flat, lining them with timbers and then filling the space with sand and rip-rap. The rails conclusively proved post-Koa subsidence of at least 18 m. The last rail, closest to ground zero, was interpreted to indicate the maximum diameter of the transient crater.

A frame used for testing cement and another set of rails outside the present crater provided additional evidence of subsidence. The structure is shown in Figure 10 and 11)., Before the blast, the cement structure was 3.5 m above mean low tide (Figure 12). Eight days after the test, it had subsided to near sea level. Today the top of the structure is at mean low tide.

Also shown in Figure 12 is another access road buttressed by railroad rails. Today the tops of these rails, encrusted by coral, are more than 1 m below low tide (Fig. 10 and 13). In these examples scuba diving and geological detective work clearly showed that not only had the crater enlarged since the blast but there also had been significant subsidence beyond the crater's margins. Additional details are included in Folger (1986).

Core Drilling

The diver-operated hydraulic underwater coring device shown in Figure 7 is patterned after that of MacIntyre (1975) and has been used extensively in Florida and the Caribbean by the USGS Fisher Island Field Station. As discussed earlier, the drill was used to sample depressed reef flat-rock around crater margins. as discussed earlier. It was also used to gain background information on cementation gradients, thickness of reef plates, and depth to the underlying Pleistocene reef surface. The drills portability allowed core drilling a few meters from the seaward edge of a Pacific atoll reef flat for the first time. In the lagoon the tripod was set up on a 10-m-deep, 30-m-high patch reef that been fractured by the Oak event and a 12-m-long core was obtained.

The device takes 4-cm-diameter cores in 1.5-m (5 ft) increments and by adding threaded lengths of drill pipe, is capable of coring to a subbottom depth of 20 m. Seawater is used for drilling fluid and is pumped down the drill pipe by a positive displacement gear pump powered by a 14-hp gasoline engine. Drilling equipment was deployed from the 8-m-long diver research vessel *Halimeda.*

The hydraulic drill was also used in the handheld mode with large-diameter (10 cm), diamond-tipped barrels to core massive coral heads for coral growth rate studies. These studies revealed that 100-year-old heads of *Porities lutea* that survived physical removal by the blast were still living and growing at pre-bomb rates. Some were less than 1000 m from a 1,750-m-diameter crater produced by a device approximately 500 times more powerful than those exploded in World War II. In another study, *P. lutea* (see Figure 13) was shown to have recruited to the margins of Koa crater within one month of the blast. Apparently, radiation did not prevent recruitment, although these corals lacked clear annual banding, suggesting genetic effects of radiation (Hudson, 1985).

CONCLUSIONS

These studies demonstrated the advantages of having diving scientists do research normally contracted to commercial or military divers. It seems highly unlikely that untrained commercial or military divers could have solved the complex geological and biological problems encountered in this study.

Underwater video proved to be an inexpensive and effective tool for obtaining and recording routine data, especially during the mapping phase using the submersible. Diver operated underwater video provided documentation in areas too shallow or otherwise unreachable with the submersible. The only limitation of diver operated video was water depth and absence of on-site verbal documentation to supplement the visuals.

An air-lift constructed in the field was especially useful for removing sediment and allowing observations not otherwise possible. The underwater, diver-operated, core drill provided data on the growth of reef flats and lagoonal patch reefs that no other method could provide. Use of the core drill was instrumental in the identification of depressed reef-flat limestone.

The manned submersible allowed collection along a vertical, shark-protected wall to a depth of 400 m. Dredges and remotely operated vehicles probably could not effectively operate and collect under such conditions.

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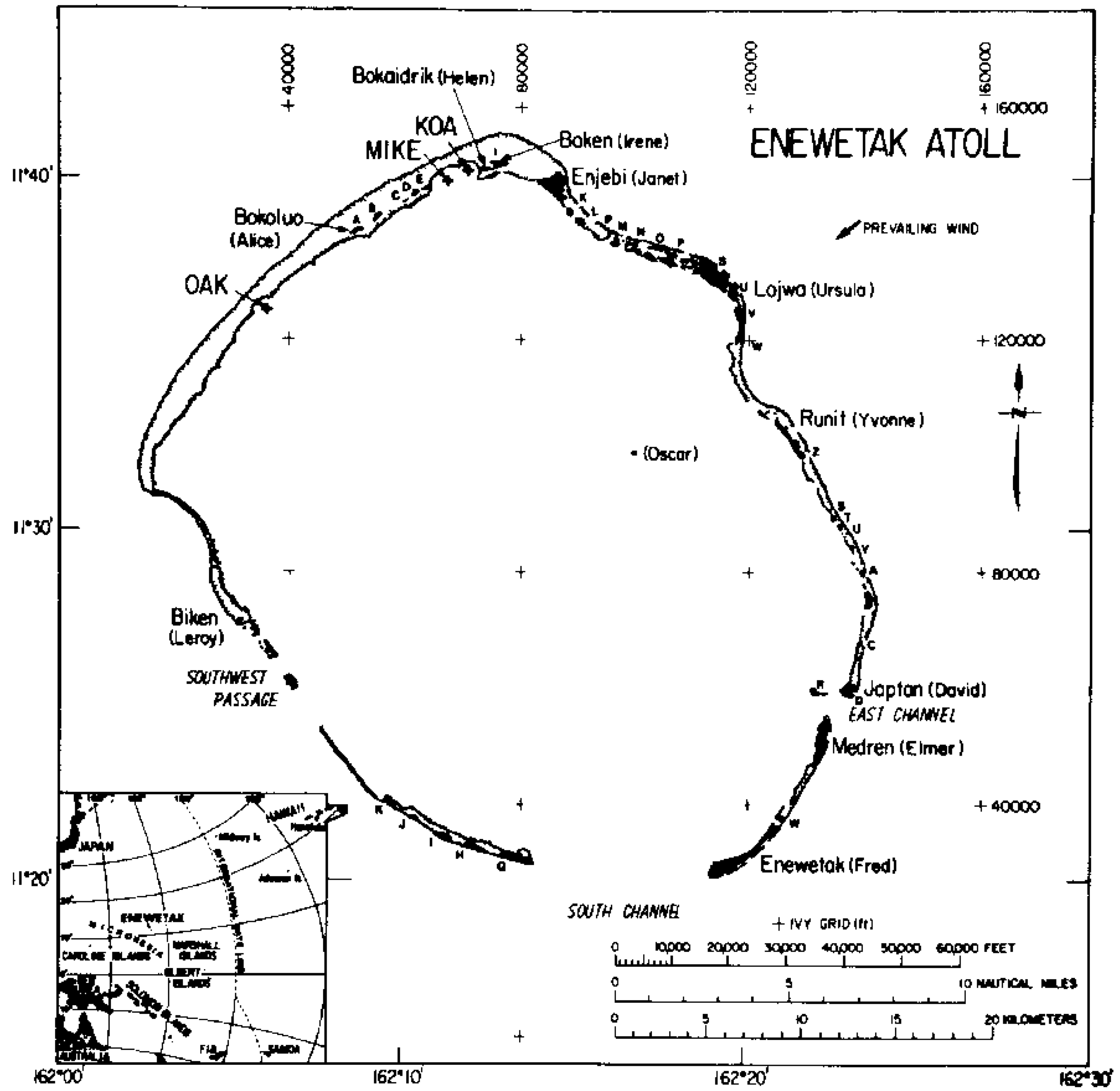

Figure 1. Map of Enewetak Atoll showing locations of Oak, Mike, and Koa craters and many of the significant islands that make up the atoll. Only Enewetak and Medren Island are populated.

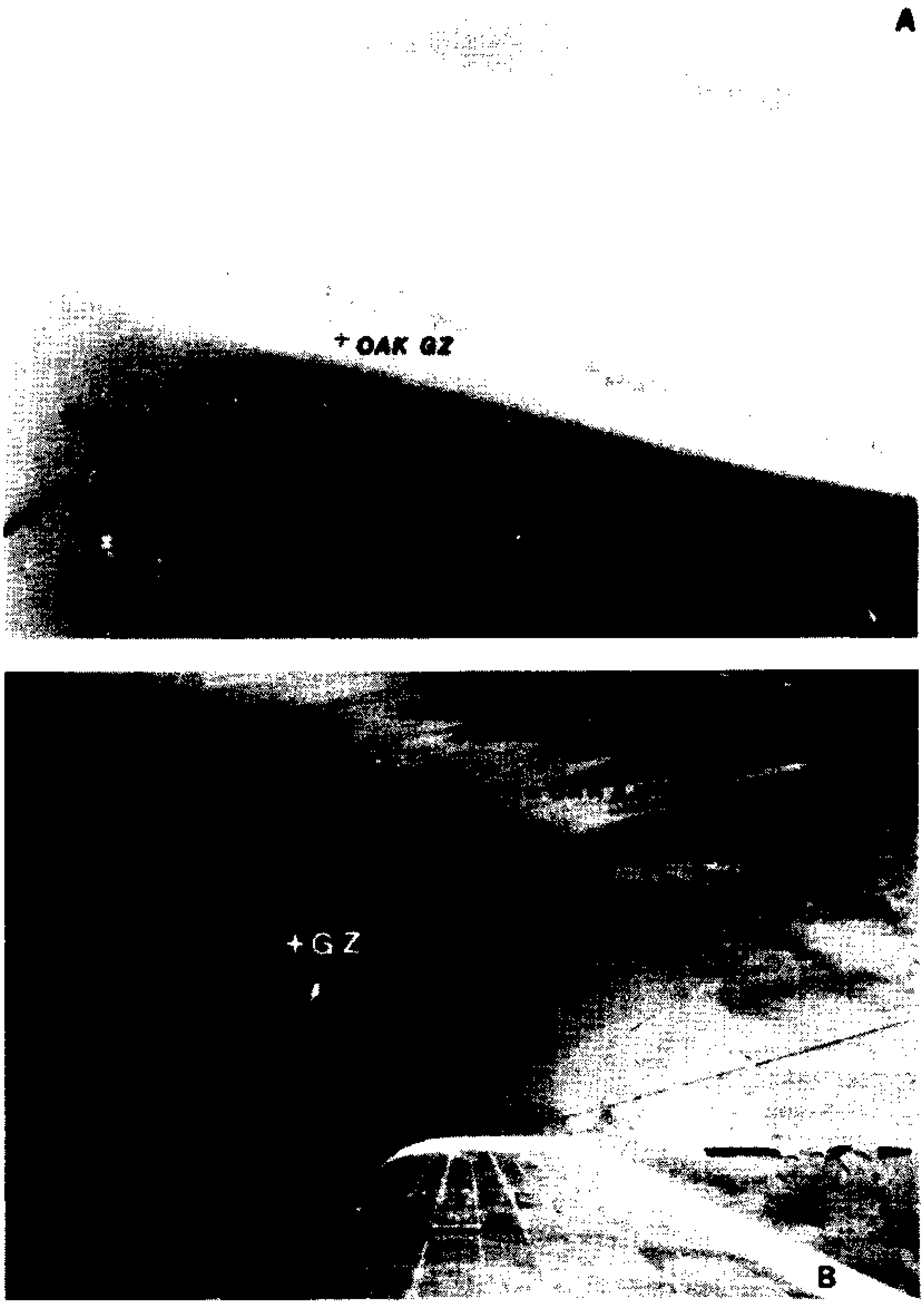

Figure 2. Oblique air view of Oak showing ground zero before (A) and after (B) the blast. Notice that location is at transition between lagoon and back edge of the reef flat.

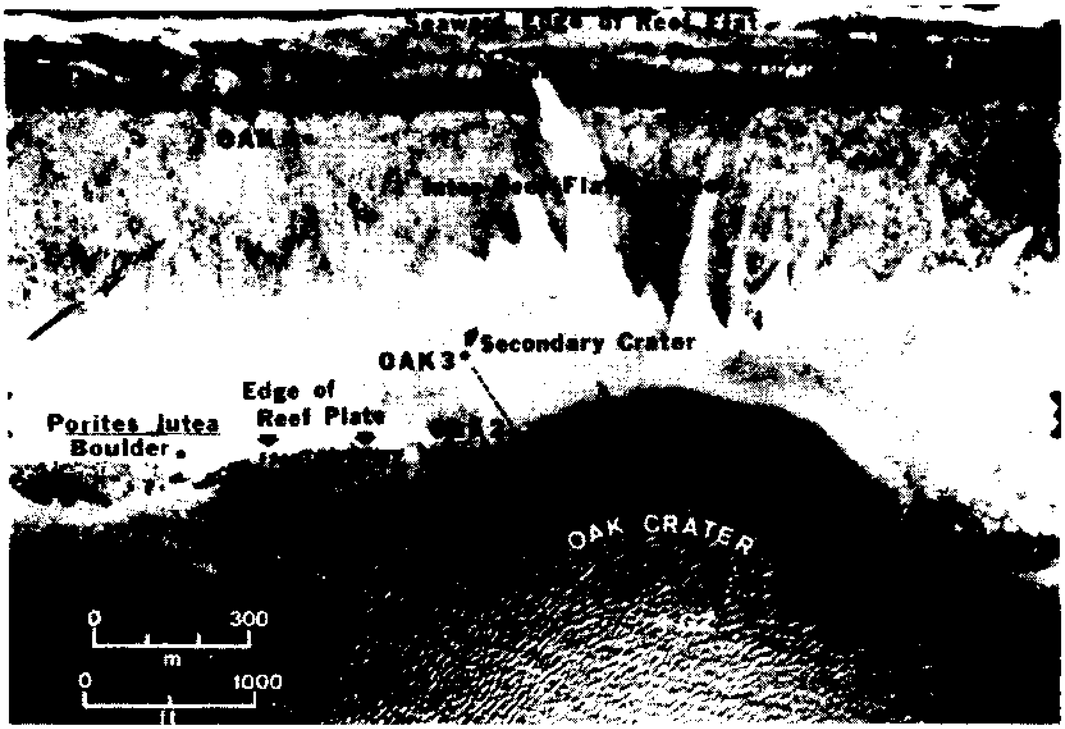

Figure 3. Vertical air photo of Oak crater showing ejecta rays on reef flat, area of depressed reef flat rock, and a small secondary crater.

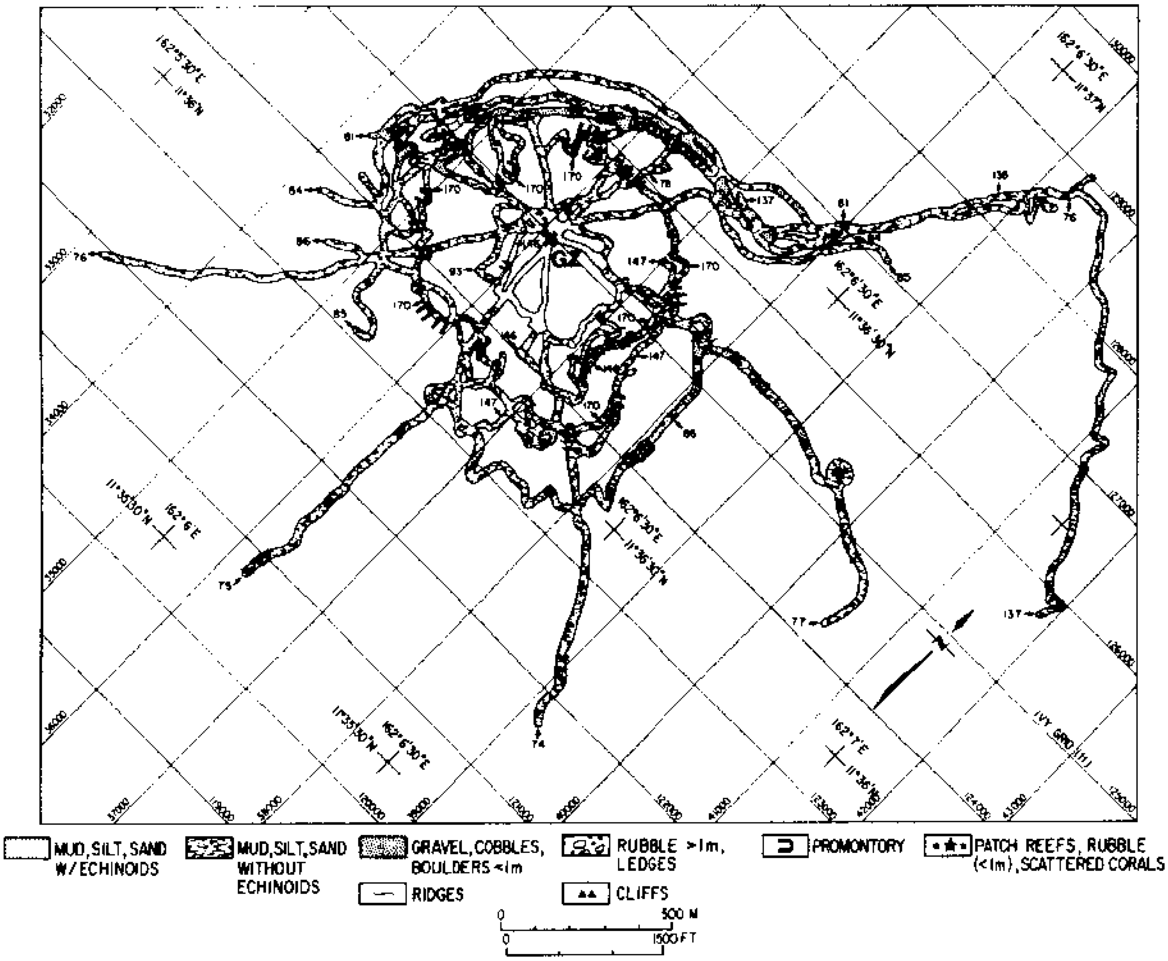

Figure 4. Map of Oak crater showing bottom sediment distribution along submersible tracts. Carbonate mud and silt are the prominent sediment components within the crater.

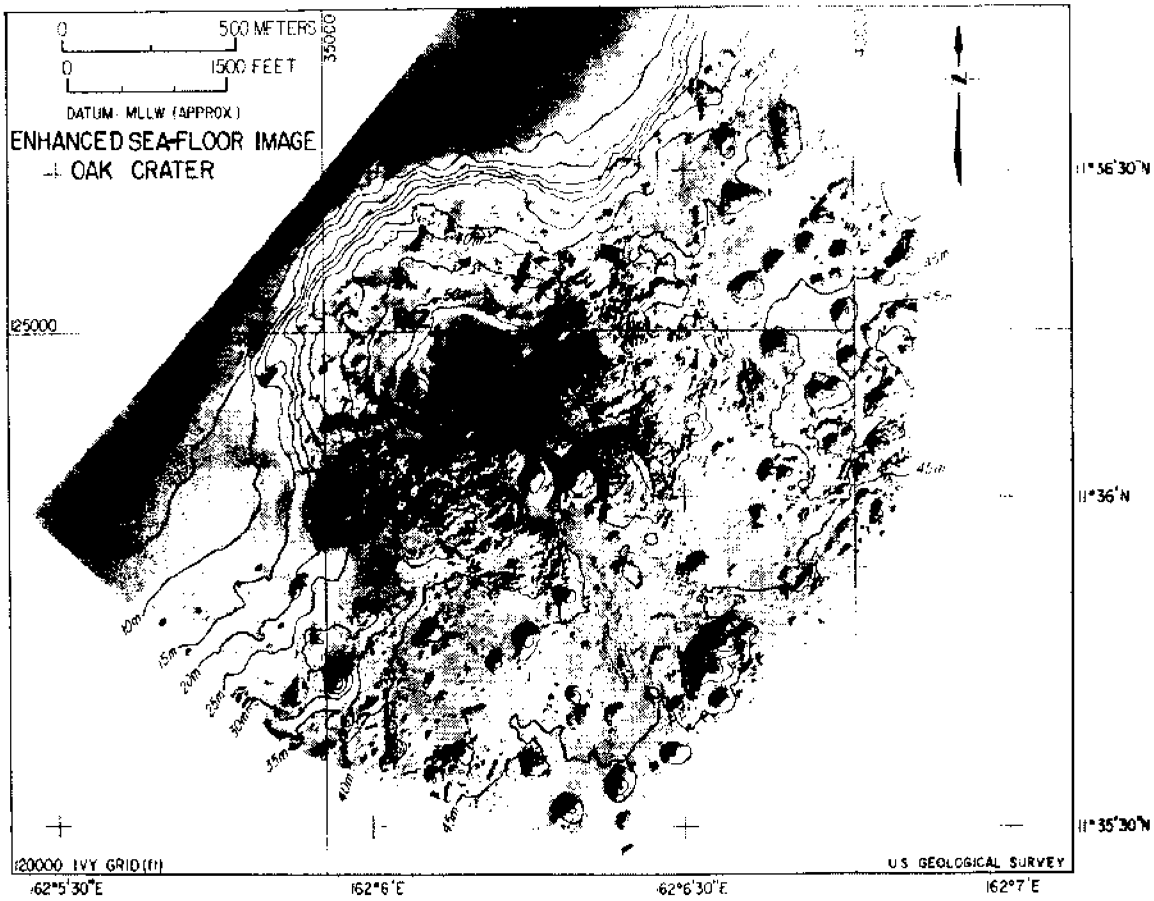

Figure 5. Enhanced image of Oak crater with superimposed depth contours. Note abundance of patch reefs and channel southeast of crater. Water depth at ground zero (GZ) was 5 m before detonation.

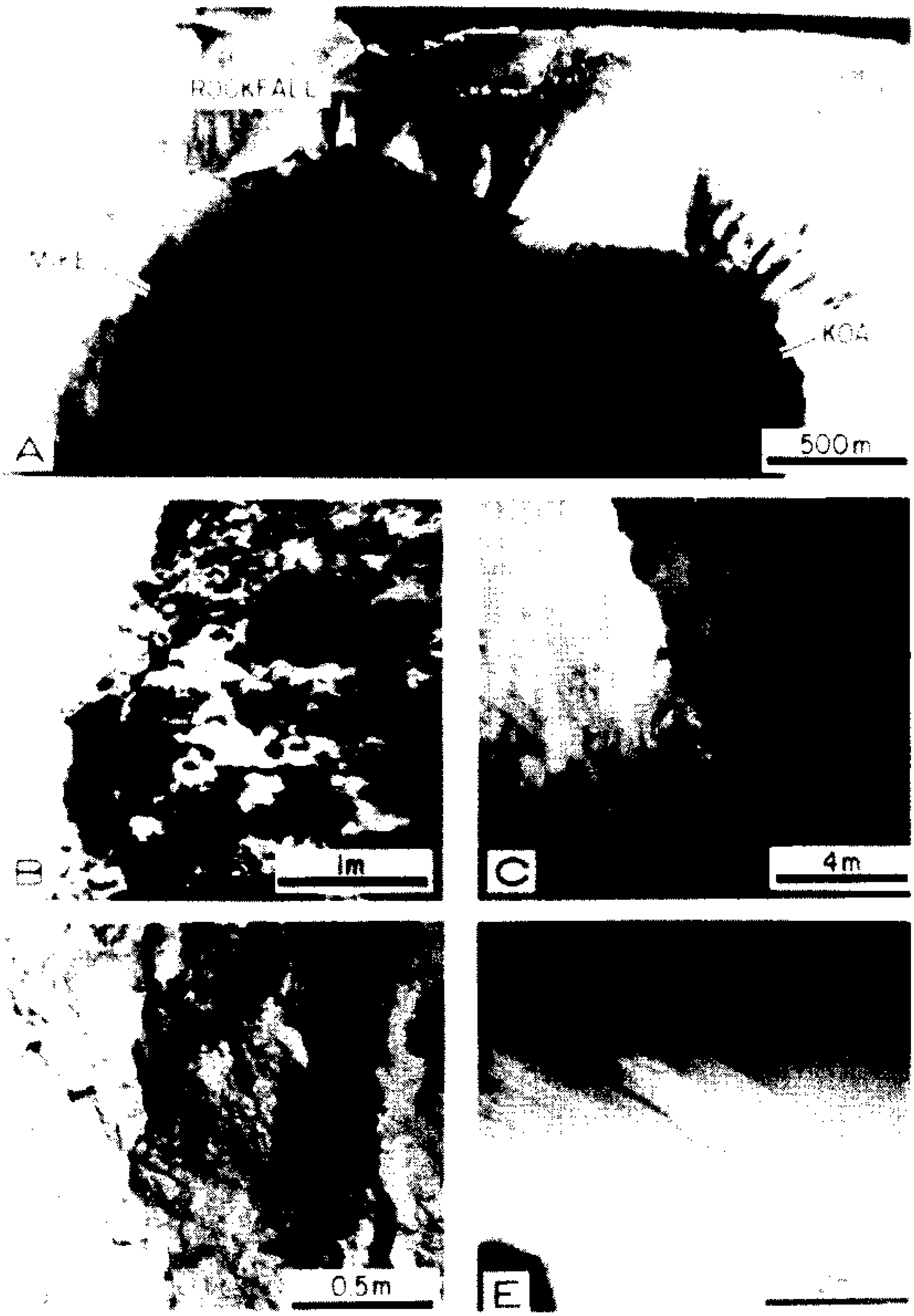

Figure 6. (A) Aerial view of overlapping Mike and Koa craters rock fall area on seaward side of atoll opposite Mike. Note ejecta rays radiating from both craters. B–E show the outcrop produced by the rockfall.

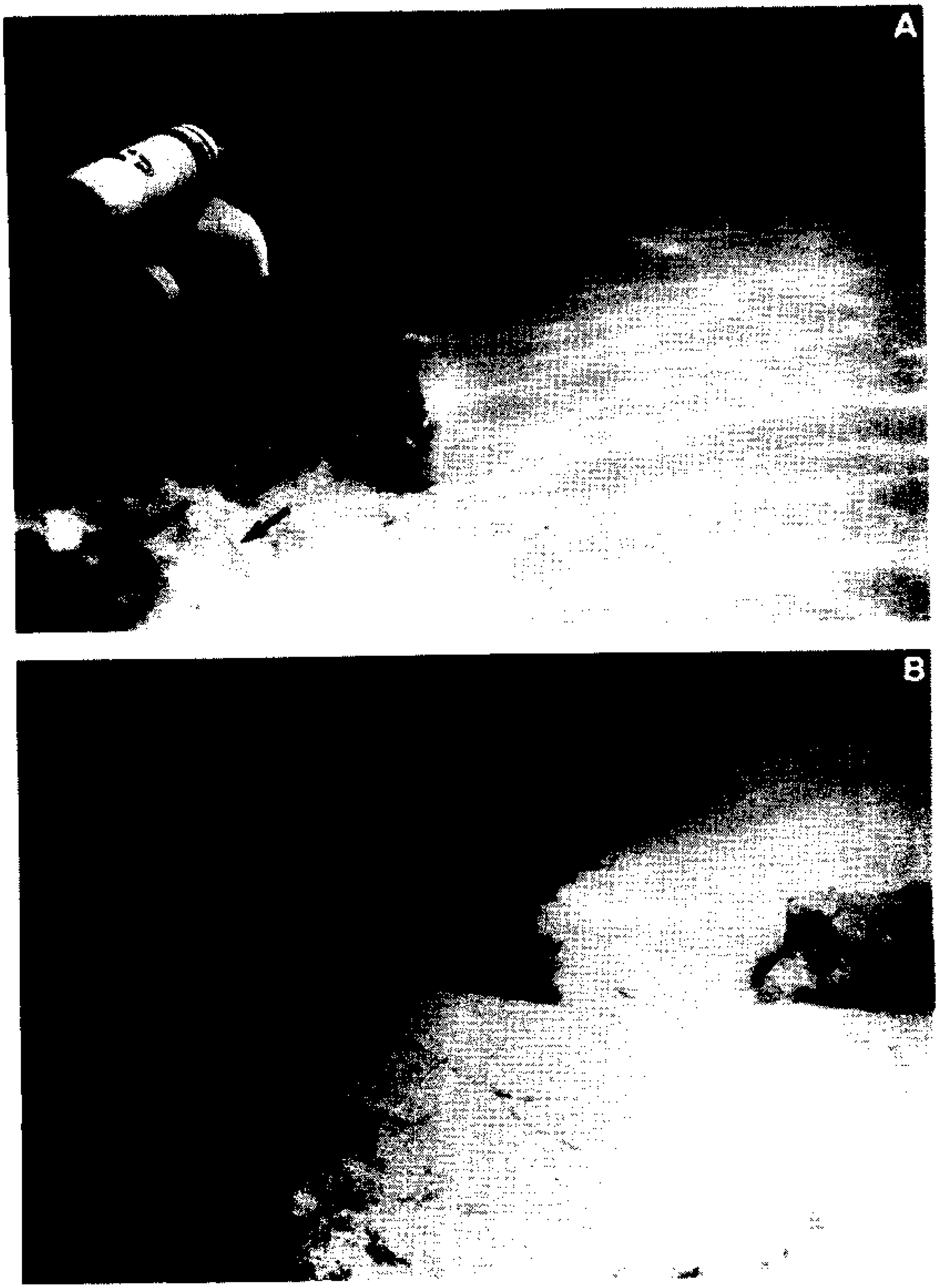

Figure 7. Two views of depressed, upturned, reef-flat limestone along margin of Oak crater. Note ripple-like features on surface of rock in A (shown by arrows). Crater is at left.

Figure 8. Drilling with hydraulic drill on depressed reef-flat limestone on flank of Oak crater at a depth of 10 m. Submersible in background. View is toward crater.

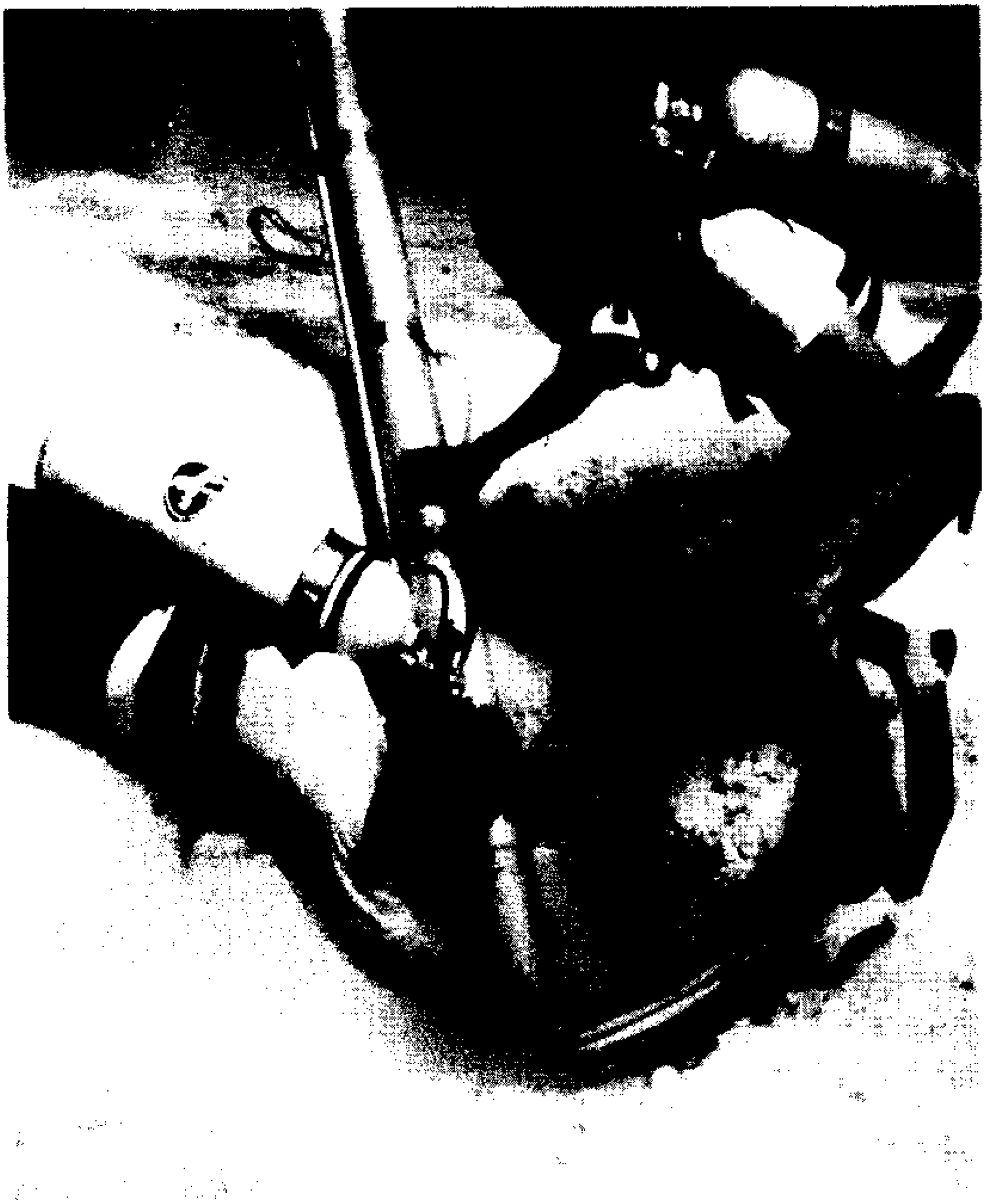

Figure 9. The air-lift being used to expose surface of reef flat rock on flank of Oak crater.

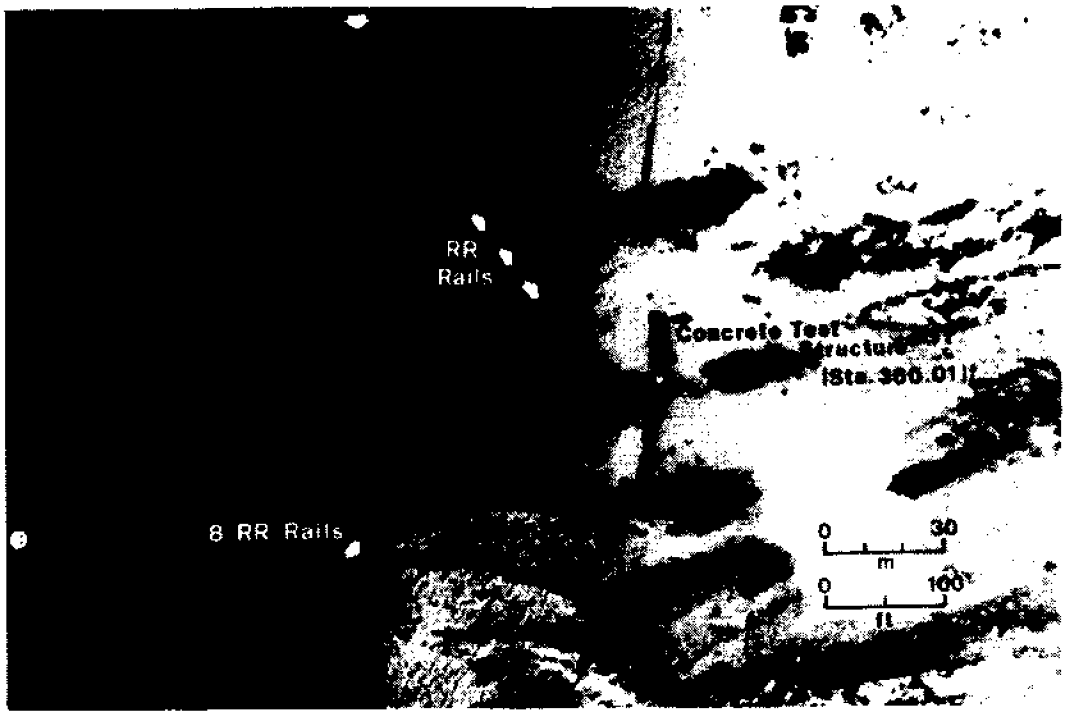

Figure 10. Vertical air view of side of Koa crater showing position of cement testing structure shown on Figure 11 and 12 and rails shown in Figure 13. Deep rails begin at x in circle in lower left side of photo.

Figure 11. Submerged coral-encrusted cement test structure near Koa crater. Surface is slightly awash at spring low tide.

Figure 12. Cement test structure, shown in Figure 7, when it was 3.5 m above sea level a few days before the Koa test. Arrow shows railroad rails used in construction of roadway to left.

Figure 13. Row of coral encrusted rails, same as in Figure 8, now 2 m below sea level. Note timbers at base of rails. Road fill was on left side of rail line.

USE OF TETHERED SCUBA DIVING TO IMPROVE SAFETY AND EFFICIENCY

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Tethered scuba diving is one of the least used and most misunderstood modes of diving available to the scientist today. Modern equipment and techniques allow safe deployment of a single scuba diver for underwater observation and sampling. Inexpensive high-quality communications equipment facilitates effective diver monitoring and data transmission. Tethered scuba diving is extremely cost-effective and is the mode of choice for many diving operations in limited visibility water, shallow water, and under ice. Tethered scuba diving has many advantages over surface-supplied diving and conventional scuba diving with regard to diver efficiency, safety, operational cost, and equipment cost. Operational and safety procedures, equipment selection, and diver training is addressed.

INTRODUCTION

Swimming and working underwater using self-contained underwater breathing apparatus (scuba) is a standard practice in scientific diving. Accepted safety procedures for scuba diving operations generally require deployment of divers in pairs (i.e., use of the buddy system). On the other hand, commercial divers more commonly use surface-supplied (or umbilical) diving equipment and commonly deploy only a single diver to accomplish the underwater task. The diver is supported by a tender on the surface or in a diving bell.

A less commonly used mode of diving is tethered scuba diving. This generally involves the deployment of a single scuba diver who is tended from the surface by means of a safety line. Tethered scuba diving is probably one of the most under-rated and misunderstood of all diving modes. The procedures and equipment used for tethered scuba diving by some search/rescue and commercial divers are considered to be haphazard by many diving safety authorities. In the scientific diving community, tethered scuba diving has often implied attaching a rope to a solo diver using a conventional mouthpiece-style scuba regulator (hookah). There was no full-face mask security, no emergency air supply alternatives, no communications (except line-pull signals), and, generally, no specific training. Tradition, lack of state-of-the-art equipment, inadequate training, economic constraints, and narrowlyscoped recreational diving influences have compromised advancement and, in some respects, safety in scientific diving.

Tethered diving has never been officially accepted by the recreational diving community in the United States. Furthermore, only a limited number of scientific divers currently use tethered scuba techniques, probably because most scientists have been trained by recreational diving instructors. Critics of tethered scuba diving include the following concerns:

- Scuba diving without a buddy is unsafe;
- The diver could be at high risk if the safety line or tether became entangled;
- The diver would not have the assistance of a buddy in the event of air supply failure or depletion; and
- The diver would surely drown in the event of loss of consciousness.

On the other hand, advocates of tethered scuba diving consider the following factors in support of the practice:

- Tethered scuba diving may only be used for *selected* underwater activities, not as a complete substitute for all conventional scuba diving or surface-supplied diving;
- The tethered scuba diver is not diving alone since the surface tender, in reality, functions as a buddy;
- Modern diving practices include the use of voice communications between the diver and tender, thus providing a means of constantly monitoring the diver's status;
- Tethered scuba diving operations involves less equipment, less deck than conventional surface-supplied diving operations;
- An organization can easily and economically outfit and train conventional scuba divers for tethered scuba diving;
- Use of a single tethered scuba diver is probably a safer practice for diving in very limited visibility water than free swimming scuba diving where buddy separation is more probable and underwater emergency assistance requirements such as sharing air are extremely difficult at best, if not impossible;
- Loss of air supply or primary regulator malfunction emergencies can easily be resolved by using scuba fitted with dual regulators or a compact secondary scuba; and

- If a diver loses consciousness underwater, the full face mask would prevent immediate drowning and loss of communications/line response would prompt the tender to immediately recover the diver and/or deploy a standby diver.

The equipment and procedures for present day tethered scuba diving are significantly different from those used in past years. The following conditions and limitations are recommended for modern tethered scuba diving operations:

- Depth is generally limited to 60 ft (except in standby diver deployment emergency);
- Communications/strength member tether must be secured to the diver's scuba or safety harness;
- A full-face mask must be used;
- An emergency or secondary air supply and/or regulator system must be used; and
- The diver must surface when cylinder pressure is reduced to no less than 500 psi (300 psi for twin cylinder scuba).

Although tethered scuba diving is not considered as acceptable as surface-supplied diving by many researchers and commercial divers, it has proven satisfactory and safe for many scientific diving operations and for standby diver application. It has been especially useful for very limited to zero visibility shallow water research where the dive team does not have a surface-supplied system available. Under such conditions the presence of a second diver is of little or no safety benefit and may even constitute additional risk.

Tethered scuba diving has also been effectively used for extremely cold weather diving from small, open boats where the deployment of two divers would have greatly complicated logistics and increased the surface exposure time. This mode has also been successfully used for under ice diving.

PERSONNEL

The minimum tethered scuba dive team should consist of no less than three persons – a tender/supervisor, a diver, and a standby diver. These individuals can develop an efficient diver rotation plan and work safely and comfortably from a small vessel. An additional qualified individual to serve as standby diver tender, record-keeping/timekeeper, and general diver aide is highly recommended.

Any competent scuba diver can be easily trained in tethered scuba diving techniques. Establishment of an acceptable training and operational tethered scuba diving program simply requires some special equipment (in addition to conventional scuba diving equipment), a slight modification of scuba diving philosophy, and a respect for both the advantages and limitations of this mode of diving. Furthermore, most competent scuba diving instructors can develop the knowledge and skill to teach tethered scuba. Since tethered scuba diving is more likely to be applied in working operations such as search/rescue and scientific research, the instructor should have a thorough understanding of the type of diving operations for which the diver is being trained.

The trained scuba diver will have to make some adjustments in diving philosophy and technique in addition to learning to use new items of equipment. The diver will have to adjust to working alone underwater and recognizing emotional and physical security in the tender above and special equipment. Consequently, competence and experience in scuba diving cannot be over emphasized.

Tender

A tender is a member of the dive team who assists the diver in dressing, donning scuba, pre-dive equipment inspection, deployment/retrieval, and post-dive activities. While the diver is under water the tender constantly tends the dive's tether to eliminate excess slack or tension. In the event of communications unit malfunction, the tender must exchange line pull signals with the diver, keep the diving supervisor informed of the diver's status, and remain alert for any signs of an emergency.

With few exceptions, the tender should also be a qualified tethered scuba diver. This insures that the tender will have a complete knowledge of all equipment and procedures. In addition, operational efficiency is highest if all members of the team can be included in a diver rotation plan. When circumstances require the use of a non-diver as a tender, it is the responsibility of the diving supervisor to assure that that individual is properly instructed in tender duties. Ideally, non-diver tenders should complete the same training course as tethered scuba divers (except for in-water activities) plus be completely familiar with scuba and scuba diving procedures. They must also be trained in general and diving-related first aid and currently certified in CPR. It is evident that one cannot simply hand the tether to a bystander and say "Will you tend the diver today?"

Standby Diver

A standby diver is required for all tethered scuba diving operations. The diver must be fully qualified and equipped to enter the water in response to an emergency at any time. The diver shall be appropriately dressed and have equipment assembled so that he/she can don all equipment and be deployed within one minute. This means that each tethered scuba diving team must have two complete tethered scuba outfits. Ideally, a second tender is also available to serve the standby diver.

The standby diver is deployed at the discretion of the diving supervisor. The standby diver functions in a lifeguard capacity ready to render aid to a distressed diver on the surface as well as under water. The standby diver is positioned at the diving station where he/she can observe the entire operational area and quickly deploy.

EQUIPMENT

In addition to standard scuba diving equipment and thermal protection, the following items shall be included in a tethered scuba diving kit:

- Demand breathing lightweight full-face mask with communications;
- Twin 72, 80, or 100 cubic foot scuba unit with dual regulator manifold or a separate 15 to 40 cu. ft. emergency scuba (commonly called a pony cylinder in scuba diving) [single cylinder scuba may be used for short and/or shallow dives provided that a dual valve system with two regulators or an emergency scuba is included in the system];
- An over-pressure relief valve must be used on any first stage regulator without a downstream second stage;
- Submersible pressure gauge on primary regulator;
- Communications/strength member tether; and
- Surface communications unit.

Mask

From a safety and communications standpoint, it is necessary to use a full-face diver's mask rather than a conventional mouthpiece-style scuba regulator. First, proper communications is very difficult with a mouthpiece-style regulator. Second, in the event that the diver is injured or loses consciousness, the mouthpiece-style regulator could easily be dislodged and lost. With a full-face mask, even if the diver is unconscious he/she could continue to receive air.

Based on personal preference, a diver or diving group may select one of several conventional surface-supplied demand breathing masks (i.e., Heliox-18, KMB-10, DM-5 or equivalent) which have been standard equipment in scientific, commercial and military diving for more than a decade or a lightweight demand breathing mask (i.e., AGA, Widolf, DSI EXO-26, or equivalent).

Most tethered scuba divers prefer to use a lighter weight, lower internal volume demand breathing full-face mask rather than the heavier, more complex commercial/military masks. These masks are constructed with either soft rubber full-face assembly or a solid support frame with a rubber face seal and are fitted with a high impact polycarbonate plastic wide-view face plate. A large, flexible nose pocket facilitates pressure equalization in the ears. The mask is secured to the diver's face using a head harness (or spider) assembly. A demand regulator is fitted to the front of the mask.

Lightweight masks do not generally include the special side block assembly for attachment of a secondary air supply as described above. However, a separate manifolding assembly is available. Communications components are fitted inside the mask with an earphone positioned in a pocket in the face seal or on a head strap. An oral-nasal mask minimizes dead air space. The lightweight masks are generally less expensive than the conventional commercial surface-supplied divers' mask and scuba divers find them to be more comfortable.

Tether

An excellent *combination safety and communications* line constructed of 7 mm nylon static kermantle rope with a tensile strength of 5800 lbs. is now available. The four communications wires are woven directly into the rope. This rope has the strength and handling characteristics of ordinary safety rope. Tying knots in the rope apparently has no adverse effects on the communications wires. Quick-connect electrical connectors are fitted to each end and special adapters are available. This special rope may be coiled or conveniently stored in and dispersed from rope bags.

The diver's end of the umbilical assembly is fitted with a large stainless steel snap shackle or caribiner to facilitate attachment to the diver's safety harness. This system allows any stress on the tether to be transferred to the diver's harness. The shackle is secured to the tether with an appropriate knot or a clamp that allows most of the stress to be transferred to the strength member. A D-ring is secured to the surface end of the assembly so that it may be secured at the diving station. This reduces the possibility of the tender and communicator being pulled overboard in the event of underwater stress.

The tether may be marked at 10-foot intervals starting at the diver's end using brightly colored tape or other appropriate marking system. This enables the tender to determine exactly how much tether has been deployed.

Communications Unit

A standard compact diver communicator is used for tethered scuba diving. Compact communicators are powered by expendable or rechargeable batteries. The tender generally wears the communicator on a belt or neck strap. A combination earphone/microphone headset is plugged into the communications box. This enables the tender to satisfactorily communicate with the diver in areas of high ambient noise levels and requires less power usage than loudspeaker systems. The tender can adjust both diver and tender volume. Some models are fitted with a tape recorder connection. Generally, any surface-supplied diver communicator may be used with a tethered scuba system; however, compact models are more convenient.

A common talk or round robin system may be used to provide all parties with simultaneously open line communications, as in telephone conference calls, without operating any controls. This system involves special wiring of the mask earphones and microphone and the use of a four conductor wire to the surface. Some current model compact communications units are designed to be used as either a two-wire push-to-talk or four-wire common talk system.

Emergency Self-Contained Air Supply Options

The tethered scuba diver has several independent options for resolving an air supply depletion or regulator malfunction situation. The diver may activate a second or backup regulator, or make a controlled emergency swimming ascent.

Keep in mind that the possibility of air supply depletion or regulator malfunction should be absolutely minimal if equipment is properly maintained and the diver properly monitors his/her air supply pressure gauge. Naturally, the primary regulator must be fitted with a submersible pressure gauge to facilitate convenient air monitoring throughout the diving operation. Unlike surface-supplied diving, the diver is solely responsible for monitoring remaining air supply. However, as in scuba diving, the diver must be trained and prepared to resolve such an emergency.

If the air supply from the primary first stage regulator is interrupted due to malfunction, the diver may activate the secondary or emergency air supply by turning a valve located on the separate manifold block attached to the scuba harness. Hoses from two first-stage regulators are attached to the manifold assembly (which may be mounted on the scuba harness). The air supply from the secondary regulator is secured by closing a valve on the assembly; the primary air supply passes through the assembly into a hose attached to the diver's second stage regulator. In the event of a primary first stage malfunction involving interruption of air flow, the emergency air supply is activated by turning this valve.

The secondary first stage is attached to one outlet on a single or twin cylinder scuba dual regulator outlet manifold assembly (i.e., Sherwood slingshot valve or dual outlet valves) or to a separate scuba cylinder (i.e., 15 or 40 cu. ft. cylinder with standard valve). Many divers prefer to use a separate scuba cylinder rather than a dual regulator manifold assembly. In the event of primary air supply depletion, the diver has an emergency air supply.

Divers working in overhead environments and locations with high risk of entanglement often prefer two scuba cylinders of equal size instead of the smaller cylinder. In this case two separate 70 to 100 cubic foot cylinders are mounted in a double band-harness system. Unlike the air management techniques that involve alternating regulators used by cave and wreck scuba divers, the tethered scuba diver conducts the complete dive as a single cylinder dive.

The second cylinder is only to be used in an emergency. Custom designed full-face masks with dual second stage regulators and air manifolding systems are now being used in wreck and cave diving. These units show great promise for improved safety in tethered scuba diving.

Keep in mind that this secondary first stage regulator hose leads to a closed valve during normal operation, not to a down-stream (or fail safe) second stage regulator as in conventional scuba. In the event of a first stage over-pressure malfunction in the secondary regulator, the complete cylinder pressure could be released into the low pressure hose causing a rupture and subsequent loss of air supply. Consequently, this regulator must be fitted with an over-pressure relief valve.

Most scuba diving instructors and scuba divers are unfamiliar with these safety relief valves that must be installed in a low pressure port on the regulator first stage. Consult full-face mask manufacturers and commercial diving equipment suppliers for acquisition of these special valves.

Safety Harness/Tether Attachment

The scuba backpack and harness assembly may also serve as the diver's safety harness. This harness is equipped with D- rings for attachment of the diver's umbilical assembly and is designed to withstand a minimum of 1000 lbs. pull in any direction. Keep in mind that the scuba harness must be securely attached to the diver. In the event of an emergency, stress placed on the harness by the tender could pull the scuba from the diver. Thus, although use of the scuba backpack and harness assembly for a safety harness appears to be a standard practice, many divers do question the safety of this method. For this reason, many tethered scuba divers prefer to use a separate body harness or safety belt worn under the scuba harness for attachment of the tether.

Standard Scuba Diving Equipment

Each diver will wear appropriate thermal protection garments, a buoyancy compensator with power inflator, fins, weight belt, a sharp knife, watch/time (for timing ascent rate) and depth gauge consistent with accepted practices in conventional scuba diving. Decompression tables may be considered optional since the supervisor/tender will monitor the dive time and inform the diver of his/her status. However, some tethered scuba divers prefer to use decompression microprocessors to monitor their dive status. Generally, each diver on a team is required to provide his/her personal diving outfit (excluding full-face mask, special scuba, tether, and communicator).

Depending on the dive depth, duration, and activity the diver may use standard single or twin cylinders taking into consideration the valving requirements discussed above for emergency or backup air supply.

TETHERED SCUBA DIVING PROCEDURES

Careful and detailed planning and preparation is the key to diving safety. The pre-dive activities involve all personnel and include the inspection and assembly of equipment, activation of air supply systems, and dressing the divers. This is, of course, in addition to survey of the task; evaluation of environmental conditions; selection of techniques, equipment, and divers; fulfillment of safety precautions; establishment of specific procedures; and personnel briefing.

Tethered scuba diving is a reasonable compromise between scuba and surface-supplied diving. A single diver can work safely and efficiently in limited visibility water. Safety is maintained through a direct connection to the surface and voice communication. The status of the diver can be monitored at all times. Operational efficiency is greatly improved since only one diver is deployed at any given time. An efficient diver rotation schedule can be prepared to achieve maximum underwater time with minimum personnel. Scientific observations can be easily transmitted to the surface and recorded on tape. The diver's time, physical status, and emotional status can be monitored by surface personnel.

Tethered scuba diving cannot be considered as a replacement for either scuba or surface-supplied diving in all situations. The tethered scuba diver is effective within the distance limitations of the tether (generally, not more than 200 feet long) and up to a depth of 60 feet. As in scuba diving, dive duration is limited by the amount of air contained in the breathing apparatus. On the other hand, the surface-supplied diver is more effective for deeper work, under more extreme environmental conditions, and in higher risk situations. In the event of entrapment or entanglement, air supply duration is unlimited. The scuba diver is more effective for swimming great distances under water and performing tasks requiring extensive lateral and vertical mobility.

Finally, equipment costs becomes a factor. Ideally, most diving tasks performed by a tethered scuba diver could be performed by a lightweight surface-supplied diver. However, the cost of outfitting a surface-supplied diving team is somewhat higher than for a tethered scuba diving team, assuming that the team is already completely outfitted for scuba diving. A tethered scuba upgrade involves purchasing two tethers, two compact communicators (or one larger two-diver model), two lightweight demand-type full-face masks, and the necessary components to convert to an appropriate independent secondary regulator/air supply system. The surface-supplied diving outfit would require additional expense for an air supply and control system and a more expensive umbilical assembly.

Tending the Diver

Tending is an art. Surface tenders should also be experienced divers or persons specially trained as tenders. The most effective assistance can be given only by a tender who is familiar with the equipment, procedures, safety precautions, conditions, and difficulties that are inherent in diving. It is the tender's responsibility to see that the diver receives proper care while both topside and underwater. He/she must check all equipment before sending the diver down.

When the diver is ready, the tender helps with dressing, checking equipment, and assists the diver to the ladder or entry point. The tender handles the tether and maintains a proper strain on the diver as he/she descends the ladder. For scuba diving type entries the tender assures that the tether plays out freely.

While the diver is submerged, the tender handles the tether, maintains communications, and monitors air usage by periodically requesting pressure readings from the diver. The usual means of communications between diver and tender is by voice intercom; however, it is important that basic line signals be memorized and practiced so they will be recognized instantly in the event of intercom failure or if apparatus not fitted with an intercom is used.

In tending the diver's tether, the tender must not hold the tether so taut as to interfere with the diver's work or movements. The diver should be given 2 or 3 ft of slack when he/she is on the bottom, but not so much that he/she cannot be felt from time to time. Signals cannot be received on a slack line; consequently, the diver's tether must be kept in hand with proper tension at all times.

Line-pull signals consist of a series of sharp, distinct pulls, strong enough for the diver or tender to feel but not so strong as to pull the diver away from his/her work. When sending signals, take all of the slack out of the line first. Repeat signal until answered. The only signal not answered when received is the emergency "haul me up", and "come up" is delayed until the diver is ready. Continued failure to respond to signals may indicate that there is too much slack in the line, the line is fouled, or the diver is incapacitated.

The tender should continuously monitor the diver's underwater timer and air supply pressure. He/she should inform the diver several minutes before the expiration of bottom time so that the diver can make necessary preparations for ascent. The tender keeps track of the diver's position by observing bubbles rising to the surface and informs the diver of his/her position relative to the boat/diving station. In addition, the tender must continually monitor the diver's activity. For example, the tender can frequently evaluate the diver's exertion by counting the number of breaths per minute. Experienced tenders will learn the diver's normal breathing rate. Significant increase in breathing rate may indicate potential overexertion. The tender may ask the diver to stop work, rest, and ventilate.

The tender may also have to serve as timekeeper. This job includes keeping an accurate record of the dive time and details of the dive. When possible, a separate timekeeper should be used or the timekeeper duties handled by the diving supervisor.

UNDERWATER EMERGENCY PROCEDURES

The tethered scuba diver will deal with underwater emergency situations in much the same manner as a conventional scuba diver, however, he/she will not have the benefit of assistance from another diver unless a standby diver is deployed. Air supply depletion or regulator malfunction is probably the most threatening to the diver. Potential risk to the diver is reduced by the use of redundant breathing systems. The diver must also be trained in purging water from a flooded full-face mask, dealing with loss of communications, and freeing a fouled tether.

Divers entering tethered scuba diving training should already be familiar with procedures such as diver rescue on the surface, stress management, accidental ascent resulting from BC or dry suit overinflation, and so on through basic scuba diving training. Naturally, proper diving procedures and common sense precautions can prevent most, if not all, underwater emergencies from developing.

SUMMARY

Tethered scuba diving is an acceptable alternative to conventional scuba and surface-supplied diving for performing many underwater tasks. This mode of diving can provide the scientific diver with a method to increase economical and operational efficiency while maintaining optimum safety. The additional equipment required for tethered scuba diving is readily available from commercial and rescue diving equipment suppliers. Most competent scuba divers can be easily trained in tethered scuba diving techniques.

The tethered scuba diving procedures and equipment discussed in this article are used on a limited basis at present. As this mode of diving gains popularity among rescue and scientific divers, techniques, equipment, and procedures for safer and more efficient diving will no doubt evolve. All divers and organizations are encouraged to use this mode of diving with a high respect for diver safety.

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For additional information consult *Tethered Scuba Diving* published by the Michigan Sea Grant College Program as part of the Diver Education Series -- Publication No. MICHU-SG-87-501. This manual includes equipment descriptions, diving procedures, emergency procedures, air supply calculation formulas, an equipment list, and a training course outline.

This publication may be acquired from the Michigan Sea Grant Publications, The University of Michigan, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109-2099 ($2.25).

THE UNIVERSITY DECOMPRESSION MONITORING BOARD

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All compressed-gas research diving activities are supervised at American Academy of Underwater Sciences member organizations by a Diving Control Board often representing departmental and administrative units rather than diving expertise. The lack of diving specialists on the Board can result in some apprehension when new techniques are proposed by the program's participants. Such Boards will naturally be inclined to restrict new advances and inadvertently may even preserve dangerous diving practices because they are time-tested.

The Florida State University Decompression Monitoring Board, composed of diving, medical and physiology specialists, is based upon a model recently described by Schreiner (1989) at an Undersea Hyperbaric and Medical Society workshop on table validation. The Florida State University Decompression Monitoring Board is designed to review proposed changes from existing research diving procedures, such as new tables, breathing mixtures, rates of ascent, and dive computers, and advise the University's Diving Control Board as to what is necessary to bring about safe implementation of the technique.

Warm Mineral Springs Archaeological Research Project requested the use of special gas mixtures to increase efficiency of their labor-intensive excavation at 160+ fsw. After careful evaluation of the available options, the Decompression Monitoring Board, in cooperation with the Warm Mineral Springs Archaeological Research Project, proposed a gas mixture, supporting documentation, monitoring procedures and diving/medical protocol to successfully continue their proposed underwater research. The new plan was approved by the Diving Control Board and has resulted in a productive season of archaeological data collection.

INTRODUCTION

Agency or institutional diving programs must be capable of flexibility and growth in response to new ideas if they are to effectively continue to support their constituents. During the past decade, university diving programs have witnessed the introduction of a variety of new technology and/or techniques such as special gas mixtures, new diving schedules, ascent rates, dive computers, and a challenge to the validity of some US Navy Diving Tables. Even casual reading of the latest edition of Diving Medicine (1990) reveals the extent diving physiology has progressed over the past decade. By American Academy of Underwater Sciences (AAUS)

Standards for Scientific Diving, the responsibility to approve new technology and techniques rests squarely upon the university's Diving Control Board (DCB). The only guideline available to this DCB for the selection of diving tables, for example, is that the table and algorithm since decompression/dive computers are permitted be as conservative as the US Navy Diving Tables (1985).

Lambertsen (1989) stated that diving is no longer performed against a single set of standard tables. Validation or consensus requirements for diving should not be standardized either, as the diversity of diving activities today (and the consequences of these activities which he lists in five tables) would make the testing unmanageable. Hamilton (1989) recommended that new procedures be given appropriate testing under laboratory conditions (presumably within a chamber or with one available) and then introduced into operational use through an intermediate closely controlled "provisional" phase. While he states that procedures, such as decompression tables, should never be considered finished, a point in time is reached when the "provisional" status is lifted and fully operational diving is permitted. Clearly, in my opinion, definitions for each phase and the decision to move from one phase of procedure validation to the next must be made by recognized representatives of the agency involved.

Many university DCBs are composed of representatives from departments that have faculty, staff and/or students that collect data underwater. They are seldom selected for their expertise on diving physiology or medicine in spite of the fact that the Board holds a responsibility to the University's President for the overall safety of the science diving program. I have witnessed a reticence on the part of DCBs to adopt new ideas because of a profound lack of experience regarding a proposed technology or technique, and causing substantial frustration among its participants. This should not be surprising since Board members (faculty in Anthropology, Engineering, Geology, etc.) may not have an adequate background to make a proper or timely determination. Unfortunately, this may encourage practices such as encouraging maximum no-stop repetitive dives on the USN Diving Tables (which is known to cause intravascular bubbling) when no-bubble tables, such as from DCIEM (Eatock & Nishi, 1987) have been available for years.

Several options exist to resolve this problem. The DCB may choose to rely upon their University Diving Officer (UDO) to advise them exclusively. This option may be limited by the expertise of the individual UDO and subject to the political motivations and pressures often placed upon a single individual. The DCB may decide to exclusively follow nationally supported "time-tested" procedures as may be advocated by organizations such as the Undersea Hyperbaric and Medical Society (UHMS), Divers Alert Network (DAN), National Oceanic and Atmospheric Administration (NOAA), US Navy or the AAUS. This option may be both legally defensible, as it represents a community standard, and prudent, as these agencies represent the bulk of the experience in a particular technology. It may not, however, be sensitive enough to serve the university's unique technical or administrative needs. Since the university assumes the liability of it's actions and benefits (or losses) from the actions that it may take, I see little reason to rely "solely" upon the judgement of another agency with little or no vested interest.

Last year I proposed to form a sub-committee to the DCB, based upon a model proposed by participants of a 1988 Workshop on "Validation of Decompression Tables" (highly recommended reading). While the immediate motivation behind creating this board was the development of deep diving procedures for the Warm Mineral Springs Archaeological Research Project (WMSARP), the long term objective was the establishment of an advisory board to the DCB on new procedures in decompression. I proposed to call the board the Decompression Monitoring Board (DMB) after a model proposed by Hamilton and Schreiner (1989).

The idea that a new diving procedure must evolve through carefully supervised phases is not new. Several agencies monitor the progress of a diving project, permitting greater autonomy as they demonstrate mastery of the required skills. This model was codified at FSU over a decade ago. Projects requiring advanced diving technology (under ice, polluted water, cave, etc.) are closely assisted for the first season while new technology and techniques are tested and a dive plan is refined. This is followed by a careful monitoring period of up to two years during which alterations are made as deemed necessary. After two years, the project is listed as fully operational and ADP supervision is reduced.

This approach is not unlike the flow diagram proposed by Dr. David Elliott during a discussion period as cited by Schreiner (1989) where mathematical modeling, table calculations, and chamber testing new diving tables is followed by an operational evaluation or "provisional" period where the tables are tested in under a "real" environment, then released for field use. The challenge, of course, is to decide when to move from the laboratory to the field and what constitutes adequate monitors for this provisional phase. These difficult decisions are left to DCB.

The purpose of this new unit, the DMB, is to advise the university's DCB on procedures in decompression and monitor them. Since from a physiological reference point the entire dive directly impacts decompression, this Board may advise the DCB on procedures as divergent as gas mixtures and mixing stations, acceptable levels of pre and pro-dive exercise, rates of ascent, in-water 100% oxygen decompression, dive computers, the medical plan, as well as the expected diving and decompression tables. Monitoring these procedures permits the required feedback necessary to adjust for new information acquired during testing and provisional phases, and to recommend that a project move from one phase to the next. At no time may the DMB assume the responsibility of the DCB.

The DMB at FSU is composed of five members appointed by the DCB for an indefinite period of time. All are voting members. When matters of the DMB are voted upon by the DCB, the UDO (holding a voting position on both Boards) must abstain from the vote. Each person was selected because he/she had experience in diving physiology, including the participant representative. At present, members of the DMB are as follows:

E. Haymes	faculty, Department of Movement Sciences exercise physiology in hypobaric/hyperbarics
Wm. Kepper	consultant, Family Practice of Tallahassee physician and trained in hyperbarics
R.W. Hamilton	consultant, Hamilton Research, Ltd., New York physiologist/decompression
G.R. Stanton	faculty, Academic Diving Program University Diving Officer, biology
W.A. Cockrell	faculty, Warm Mineral Springs Arch. Research Proj. program participant, archaeologist

A Special Gas Mixtures for Science Diving Workshop, sponsored by the ADP, with special assistance from WMSARP, was held in March 1989 (Stanton, 1990a). During the workshop other-than-air breathing alternatives were presented and successfully used on dives to 100 and 150 feet. Prior to the formation of the DMB six months later, numerous sessions were held between consultants, faculty and members of the DCB at FSU discussing the advisability and etiology of using trimix (nitrox had already been established on campus the previous year) as an alternative breathing mixture to air for depths below 150 fsw.

The newly formed DMB focused on the WMSARP request for dive clearance to depths from 150 to 200 feet for several reasons. Their Legislatively funded project was a high profile and well documented research effort under the Anthropology Department (strongly justified as a university endeavor, [McDonald, 1990; Cockrell, 1990]). Their site was ideally suited for a trial project as it was warm, stable, and logistically simple (Smith, 1986; Cockrell, 1988). Their requirements were not unlike others soon to be proposed in the foreseeable future (cave research). And their willingness to cooperate provided everyone with the opportunity to develop what was hoped to be a model for future special gas mixtures projects.

During the Fall semester of 1989, the DMB met formally at least six times, and informally in smaller groups dozens of times. Individual members of the Board traveled to the Springs (over 300 miles south of Tallahassee) at various times to meet with staff and consultants to the project. While not all meetings were cordial, the resulting recommendations, documents and administrative structure bear witness to the sincerity of all those who participated in their creation.

Additional advice beyond the confines of the Board was often sought. Legal opinion was sought regarding the question of public access to the on-site recompression chamber. Clarification of the definition of a diving injury and the advisability of discretionary treatments from our Office of Environmental Health and Safety resulted in a safer medical backup structure. Acceptance of the recommendations of the Validation Workshop regarding "provisional" status during operational dives based upon the DCAP algorithms was secured from FSU's Human Subjects Committee (HSC). The HSC was particularly willing to exclude the WMSARP dives from their control because the purpose of the research was archaeology, not diving physiology, and that the dives would be closely supervised and monitored with the ability to restructure the schedule if warranted. Staff requirements and their supervision were hammered out with the Anthropology Department Chairman until all parties were satisfied that both the safety and research needs of this project were adequately met.

Additional training (chamber operations) and monitoring technology (doppler) was recommended and secured for the ADP and WMSARP staff. I spent a week training with DCIEM in Toronto while Dr. Crosson (Delta P) spent time training at the springs, both using the latest Techno Scientific Ltd. ultrasonic doppler technology available. My assistant and Dr. Kepper spent a week at Hyperbarics International taking a course in hyperbaric medicine. The newly hired diving supervisor held a week long chamber course at the site.

Appropriate life support technology was recommended for the gas mixtures proposed, and adjusted as the site restrictions dictated (such as the location of the chamber, use of an in-water bell, mixing gasses on site, etc.). A medical plan was drafted (Kepper, 1990), revised and ultimately approved. Additional consultants were brought in from Reimer Engineering and Delta P to assist in the installation of the existing chamber. Air testing was provided by the Research Diving Program at the University of Florida through our terms of reciprocity.

Provisional diving and decompression tables based upon the DCAP algorithm for a trimix (21% O_2, 40% He, 39% N_2) were presented and approved after initial testing and field trial data was presented and examined by the Board (Hamilton 1987, 1990a, 1990b). Over the brief four week diving season, post dive doppler monitoring provided data back to the Board on a weekly basis with telephone discussions as needed. This data was forwarded to members through the mail or if considered critical, through a medical FAX network described in the medical plan.

An excellent example of the continued success of the DMB is cited below. Dr. Larry Abele proposed to observe and collect a new class of Crustacea (Remepedia) found in saline pockets at 95 fsw over 900 feet back in terrestrial caves in the Yucatan, Mexico. In 1988, he was able to spend less than 15 minutes maximum on air at the site because of the swim and available gas on his back. In 1990 he proposed to use nitrox and in-water 100% oxygen decompression, and increase his bottom time to 120 minutes with a decompression obligation of 43 minutes. Thirty six percent nitrox tables were generated by Hamilton (1990c) which permitted up to 180 minutes at 95 fsw with a maximum of 76 minutes of decompression (20/10 fsw stops on 100% O_2). The FSU DMB was asked to evaluate the proposal and associated tables. They found them acceptable for provisional status with some additional recommendations. Doppler monitoring and additional training in nitrox, and staging (transport of more than just the bottles on your back) were recommended. Training in both areas was completed by the ADP staff prior to data collection. The quality and availability of oxygen in Mexico was questioned and resolved prior to departure. A report was requested by the DCB regarding the dives and monitoring data for their next meeting (Stanton, 1990b).

As the Decompression Monitoring Board enters it's second year, it faces new challenges, including recommendations for which dive computers are advisable for use at FSU and guidelines on how to use them, alternate air diving tables such as DCIEM, rates of ascent for various gas mixtures, continued discussions regarding in-water 100% decompression, acceptable levels of intravascular bubbles, and testing for patent foramen ovale, just to name a few. A project to study the hydrology of the Woodville Karsp has requested changing over from air to trimix for their deep work in local caves. Guidance for some of these issues is available from AAUS and others and no doubt will make the job easier. However, from the DCB's perspective, seeking the recommendations of a panel of resident experts is far better than saying no.

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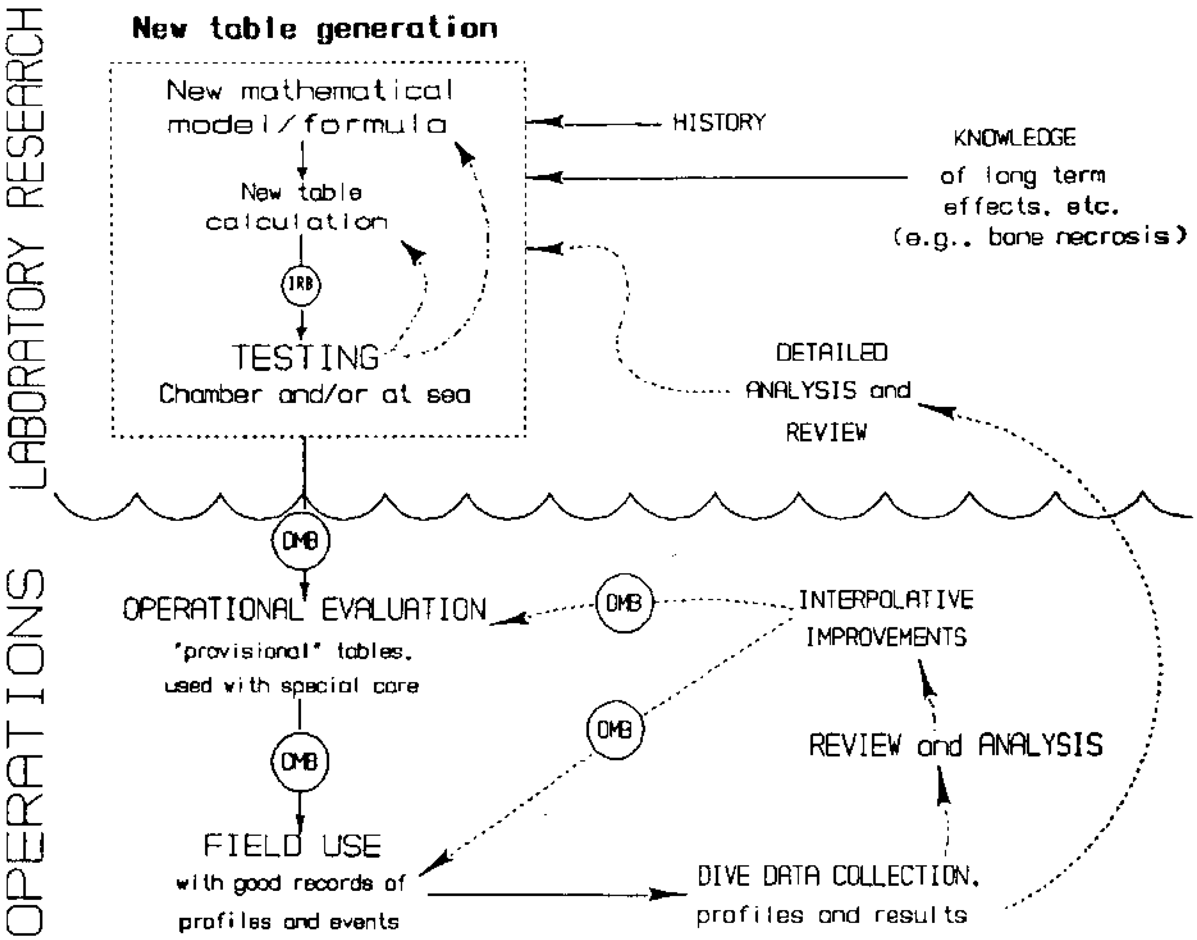

Summary Figure 1. Flow diagram of the decompression table development and validation process. The upper part of the diagram is by intent research and subject to "informed consent" procedures. The lower half is operational, and is considered to be within the job description of the divers. Solid arrows show flow of information, dotted arrows show feedback, and those with circles imply some judgemental approval by the Institutional Review Board (IRB) or the "DMB," a competent authority (board or committee) within the organization conducting the dives; it might be called the "Decompression Monitoring Board."

IMPACT OF RECREATIONAL DIVERS ON CORAL REEFS IN THE FLORIDA KEYS

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Recreational divers were systematically observed in the Florida Keys between May 10 and August 13, 1989. A total of 206 divers were observed during 66.6 hours of diving. Divers wearing gloves were responsible for 72% of the 1164 interactions observed. Out of the 135 scuba divers, 26% had one or less interactions with corals; 10% had 11 to 20 interactions; and 4% had 30 or more interactions per 30 minutes of diving time. Of the 71 snorkelers, 61% had one or less interactions with corals and none had more than 5 incidents. However, snorkelers treading water stir up large clouds of sediments and are more apt to stand on corals than scuba divers. Wilcoxon Two-Sample Tests show that divers with gloves have significantly higher numbers of interactions with corals than divers without gloves, that men have more interactions than women, and that scuba divers have more interactions than snorkelers.

INTRODUCTION

The beauty, diversity and uniqueness of the coral reefs of Florida have attracted large numbers of visitors from all over the world. Coral reef usage at the Looe Key National Marine Sanctuary (LKNMS) has increased 300% in the last 5 years (Figure 1); from 17,483 people in 1985 to 54,691 people in 1989 (Sanctuary records). This increase in coral reef use and concern over the degradation of the reef system along the Florida Keys (Tilmant and Schmahl, 1981, Rogers, 1985) has raised the question of how recreational divers impact the areas in which they dive. Sanctuary management and conservation organizations need to know whether repeated touching of corals by coral-reef users is sufficient to damage coral tissue or make it prone to infection or necrosis (Miller, 1988) so that appropriate steps may be taken to protect the only living reef adjacent to the Continental United States.

Diver damage to coral reefs is frequently masked by natural events and is difficult to assess. (Tilmant et. al., 1981, Jaap et. al., 1988). However, surveys of areas in the Key Largo National Marine Sanctuary have shown significant changes in diversity and populations which frequently indicate a dysfunction within the system that is the result of ecological stress (Dustan and Halas, 1987). To determine if divers are an aspect of this ecological stress, it is necessary to ascertain how divers behave in the water.

Until recently, the major human damage to the reef was thought to be anchor damage and boat groundings (Brown and Howard, 1985), diver damage was considered negligible. However, with the recent increase in the diver population, diver impact could be an important factor. To determine if this unknown human factor is related to reef stress syndrome, it is necessary to answer these questions: 1) How do stony corals and octocorals react to the repeated physical contacts with divers. 2) What is the frequency and nature of the physical contact that users of coral reefs make with reefal organisms? 3) Is this physical contact sufficient to add to the ecological stress the reefs are experiencing? Two of these questions are beyond the scope of this paper and will be dealt with in a companion study. This paper will address the question of frequency and nature of the interactions of the recreational diver with coral reef benthos.

METHODS

The Looe Key National Marine Sanctuary (LKNMS) core area located about three miles south of Big Pine Key was the primary study site, but divers were also observed in the Key Largo National Marine Sanctuary, Sombrero Reef off Marathon, at Eastern Dry Rocks, Western Dry Rocks and Sand Key in the Key West area (Figure 2). These dive sites were chosen because of their popularity with both local and visiting divers. All observations were made from charter dive boats or concession boats operating from Sanctuaries and include both scuba divers and snorkelers. Subjects were chosen at random from divers on the dive boats.

The observed interactions between diver and corals were 1) hand on the coral to steady or to help the diver gain control, 2) kicking or brushing a coral with the fins, 3) standing on corals (especially snorkelers), 4) grabbing corals to pull themselves through the water, 5) rubbing against a stony coral with any part of the body, 6) hitting a coral with the scuba tank or other pieces of equipment and 7) creating sediment clouds.

To quantify the incidents, each interaction was recorded on a prepared slate. Damage to corals was visually evaluated and recorded, i.e. broken skeleton or the scrapping away of polyp tissue. Sediment clouds generated by divers were ranked as low, moderate, or high. Additional information included duration of dive, diver experience, buoyancy control, whether gloves were worn, meteorological conditions, and the quality of the briefings given by the captain or dive master.

To standardize observations, data on each dive was adjusted to 30 minutes. The interactions were then ranked into one of 4 categories:

a - 0 to 1 incidents
b - 2 to 10 incidents
c - 11 to 20 incidents
d - > 20 incidents

Data were compiled into tables listing diver (scuba or snorkeler), rank, sex, type of incident, whether with stony coral and/or octocoral, total number of incidents, and whether gloves were worn.

A Krustal-Wallis non-parametric analysis was applied because of the skewed distribution to show significant differences between groups. A Wilcoxon Two-Sample Test was applied to determine significant differences within groups (Sokal and Rohlf, 1981).

RESULTS

A total of 206 divers were observed, including 113 men and 93 women, during 66.6 hours of diving time with a total of 1164 interactions, standardized to 1027 interactions. A group of 65 snorkelers was observed at the Key Largo National Marine Sanctuary and will be discussed separately. Their interactions were not included in the statistical analysis.

Table 1: Ranking of divers observed, including number of people and percentage of each group (in parentheses).

RANKING	TOTAL DIVERS	SCUBA	SNORKEL
a (0-1 incidents)	78 (38%)	35 (26%)	43 (61%)
b (2-10 incidents)	104 (50%)	76 (56%)	28 (39%)
c (11-20 incidents)	14 (7%)	14 (10%)	0
d (> 20 incidents)	10 (5%)	10 (7%)	0

Table 1 lists the totals and percentages of individuals in each category. Of the snorkelers, 41% had no interactions compared to 10% of the scuba divers. The average number of incidents for snorkelers is 1.1 (n=71, standard deviation = 2.7) The average number of interactions of the scuba divers is 7.0 (n = 135, standard deviation = 15.7). Of the 1027 standardized incidents or interactions, 951 were committed by the 135 scuba divers while only 76 incidents were by the 71 snorkelers. The number of scuba divers is almost double the snorkelers, but the number of incidents by the scuba divers is 12 times the number by the snorkelers.

Table 2: The number of incidents by type of diver, sex and whether gloves were worn.

DIVER	SEX	GLOVES	NO GLOVES	UNREC	TOTAL
Scuba	Male	500 (n=50)	96 (n=21)	55 (n=14)	650
	Female	232 (n=37)	25 (n= 7)	45 (n=12)	300
					951
Snorkel	Male	5 (n=1)	34 (n=33)		39
	Female	5 (n=1)	32 (n=36)		32
					1027

Table 2 gives the number of incidents divided into type of diver, sex, whether gloves were worn and the total interactions. UNREC are the scuba divers of which no record was made if gloves were worn. The Krustal-Wallis Test of difference of location showed that there is a significant difference between the groups (df=7, P. <.001). The Wilcoxon Two-Sample Test showed significant differences in that: scuba divers had more interactions than snorkelers (n=206, t=8.1 P <.001); divers with gloves had more interactions than divers without gloves (n=180, t=9.8 P <.001); males had more interactions than females (n=206, t=20.6 P <.001).

Table 3: Number of interactions per group with corals and octocorals.

Diver	Stony Corals	Octocorals	Total
Scuba	629	312	942
Snorkeler	66	19	85
Total	695	331	1027

Table 3 shows the number of interactions by both types of divers toward corals or octocorals. Scleractinian corals were touched more often than soft corals or octocorals: 68% of the observed encounters were with scleractinian corals as compared with 32% for octocorals.

More than twice as many incidents were recorded late in the summer than early, 173 incidents by 36 divers from May 15 to June 27, as compared to 424 incidents by 39 divers from July 15 to August 15. The early summer divers were usually out-of-state while the late summer divers were in-state. Two divers with the most interactions were from Miami and West Palm Beach.

Diver-caused breakage included a total of six breaks in three different events or 0.6% of all incidents. The number of people (3) who broke coral is 1.4% of all divers. Corals broken were a small tip from a branch of an *Acropora palmata*, one branch of *Acropora cervicornis* and one incident when four blades from one *Millepora* were broken.

The most frequent interactions were the "finning", with 704 incidents and the "push off", with 153 incidents. The two most common interactions of snorkelers is standing on corals and the vigorous treading of water that stirs up large amounts of sediment when in shallow water.

DISCUSSION

A healthy reef is not only an esoteric and ecological necessity, but an economic one as well. A healthy reef system supports large fish populations, provides a genetic diversity reservoir, and is a renewable natural resource that encourages the economic benefits of tourism (Van't Hof, 1985). In Monroe County a viable, healthy reef system is of vital necessity that supports an economy dependent on both fishing and tourism.

A moderate amount of perturbation is a natural phenomena that is believed to maintain the high diversity of the coral reefs and from which many systems recover relatively quickly, i.e., hurricanes and large storms (Shinn, 1976; Tunnicliffe, 1981). But hurricanes are episodic events, while human impacts are much smaller but chronic over long periods of time. Brown and Howard (1985) states that stress over time will decrease diversity causing the fragile and rarer corals to disappear.

Divers inflict low-intensity, long-term stress on coral reefs by touching and breaking corals, by increasing suspended sediment, and by eutrophication of the water column. In a reef already stressed these acts can have serious repercussions. A simple touch or scratch can trigger what is called a "Shut Down Reaction" in corals that can kill a coral head in a matter of hours . This reaction is very contagious and can pass to other corals, possibly killing an entire reef (Antonius, 1977, 1981).

Breakage of branching corals can be utilized by some corals as a means of asexual reproduction (Szmant 1986, Bothwell 1981). Following hurricanes recovery of *Acropora* stands within 2 to 3 years is possible because of asexual reproduction (Shinn, 1976). However, fragment size is important in survival. The larger the fragment, the higher the survival rate (Bothwell, 1981). Diver breakage usually consists of small fragments from the tips. Size is also important in sexual reproduction in that corals must be at least 100 cm square to reproduce (Szmant, 1986). In small coral colonies, breakage would reduce the size and thus retard the ability to reproduce sexually.

When a coral is touched, brushed or stood upon, mucus is removed. This mucus layer protects the coral polyp from the harmful effects of the environment by increasing the polyps resistance to infection and bacterial attack (Crossland et al., 1980). Irritation caused by the repeated removal of the mucus layer is stressful and can cause the coral's mucous secretory cells to undergo sublethal changes (Peters et al., 1981). (A study to determine the impact of "touching" on corals is in process and will be completed by fall 1990).

Recreational divers who just want to "look", as opposed to divers with a purpose, i.e., photography, shelling, artifact collection, lobstering and/or spear fishing, have fewer contacts with corals; and snorkelers have less contacts than scuba divers since most snorkelers are just "looking". Except for one case, all the c-ranked divers were experienced, proficient divers who dove for a specific purpose. The one exception was a diver who was totally inept in the water.

Most observations were conducted in protected Sanctuary areas. The observations made in non-protected areas were limited to 12 people with a total of 68.0 interactions. While this number is not sufficient to show that divers in non- protected areas have more interactions, two of the divers had more than 25 interactions each. However, if these observations were expanded, I believe that divers in non- protected areas would have significantly more interactions than divers in protected areas.

This study shows that 5% of all recreational divers have more than 20 incidents per 30 minute period. Sanctuary personnel at the LKNMS estimate that about 3% of the diving public they observe are have "high" rates of impacts when diving in the core area (personal communication). This slight difference could be attributed to differing interpretations of "high" impact and to the time restraints imposed on the officers by other duties.

An additional concern associated with diver impact on Sanctuary reefs is the influence both the divers and their boats have on water chemistry. For example, on an optimum day, more than 300 divers may use the 1200 by 200 meter core area of LKNMS. Since reefal waters are naturally nutrient poor, 300 divers urinating in the water over the reef could increase the nitrogen concentration of the water by 25 to 50%. Kinsey and Davies (1979) experimentally documented that fertilizing a reef can reduce rates of coral calcification while stimulating algal growth. If divers are damaging corals by chronically and inadvertently fertilizing heavily used reefs, this problem can be reduced by educating divers and concession operators that metabolic wastes should be disposed of in sewage treatment systems.

The coral reefs of Florida are suffering from a stress related syndrome. Clearly, divers could be a part of that problem. To minimize diver effects, I suggest that a "one meter" rule be introduced, i.e. that divers keep at least one meter distance from all live biota. I further recommend that gloves be eliminated since there is a strong correlation between the number of incidents with and without gloves. Ankle weights should also be discouraged to lessen the possibility of sediment clouds. Dive instructors should be encouraged to improve education on the value of coral reefs and what they are, and to improve diver training in the area of buoyancy control, overweighting should be discouraged. Most of all, increase the amount of reef under Sanctuary control. My observations, though unproven, indicate that divers on Sanctuary reefs are more careful and less apt to touch.

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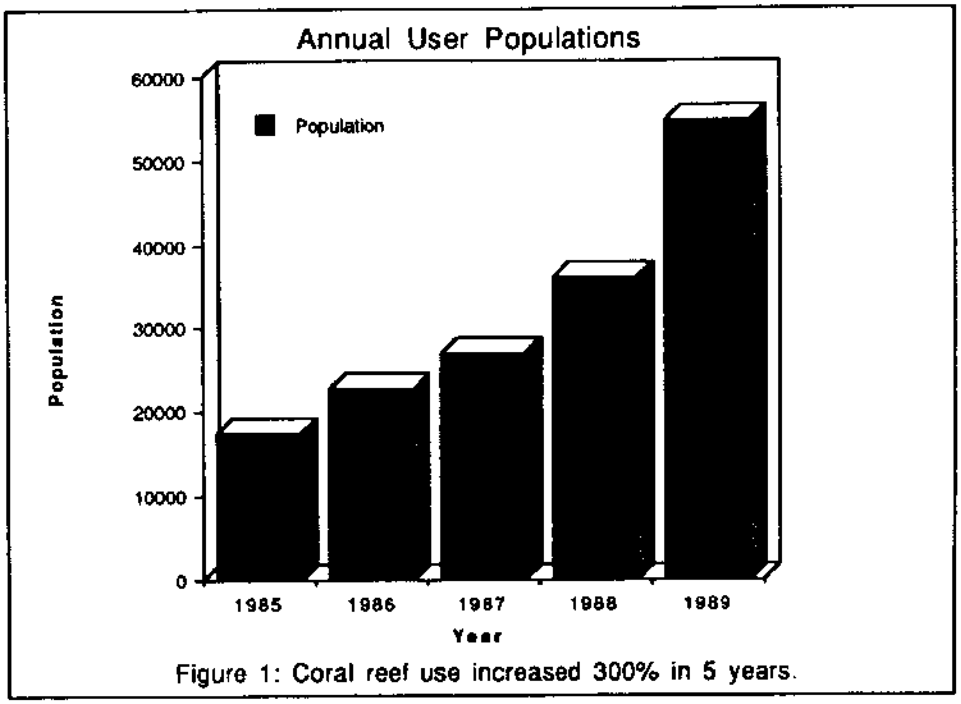

Figure 1. Annual user populations at Looe Key National Marine Sanctuary.

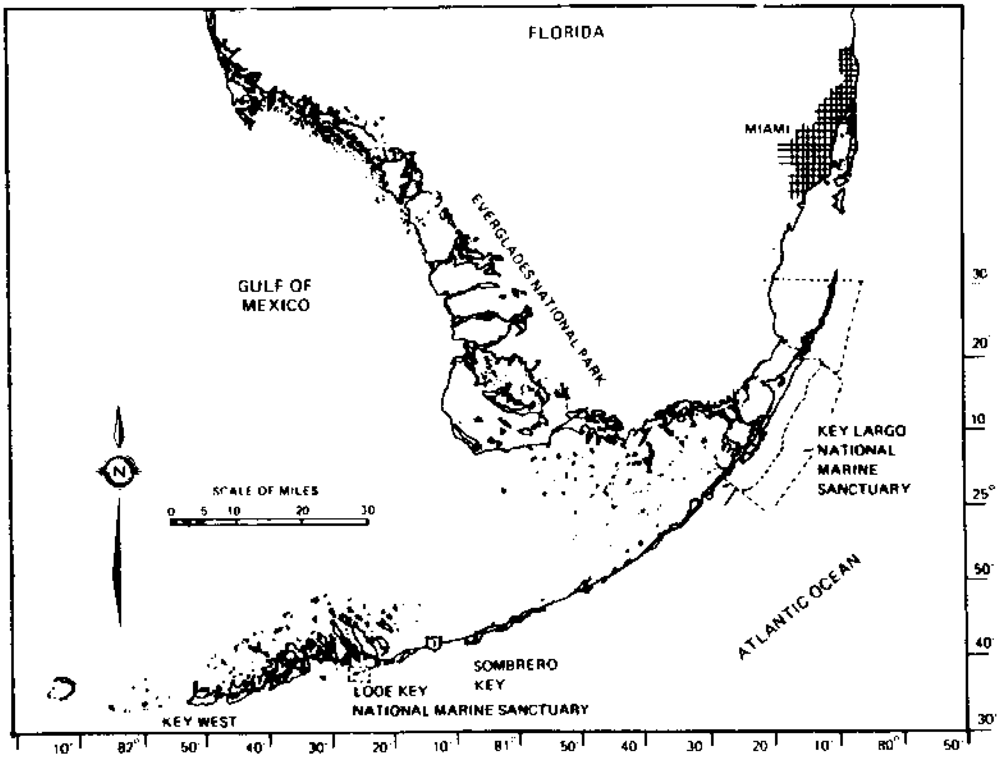

Figure 2. Diver observation sites in the Florida Keys. (Jaap, 1984)